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Interactive Virtual Environments: Adaptation to virtual hand position

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In voorgaand onderzoek (Werkhoven & Groen, 1997) heeft TM reeds aangetoond dat *directe* manipulatietechnieken (het op natuurlijke wijze met een virtuele hand grijpen en verplaatsen van voorwerpen) sneller en nauwkeuriger zijn dan traditionele *indirecte* manipulatie (via muis/cursor interactie). In het huidige onderzoek is bestudeerd of taakprestaties verminderen wanneer de positie van de virtuele hand niet precies correspondeert met die van de echte hand en of het werken met een niet corresponderende virtuele hand tijdens onderdompeling in VE de oog-hand coördinatie bij terugkeer in de werkelijke wereld beïnvloedt.

Er is een prisma-adaptatie paradigma gebruikt om de na-effecten van de adaptatie van oog-hand coördinatie in VE te kwantificeren. Er zijn pre- en post-testen uitgevoerd om de aanwijsprestaties in de werkelijke wereld te meten. Tussen pre- en post-testen werden participanten ondergedompeld in een interactieve virtuele omgeving waarin de virtuele handpositie opzettelijk verschoven was over een afstand van 10 cm ten opzichte van de echte handpositie. Door de resultaten van de pre- en post-test te vergelijken werden mogelijke (negatieve) na-effecten van de adaptatie van de oog-hand coördinatie aan het licht gebracht. Na-effecten werden gemeten in het horizontale, verticale en diepte-vlak van de virtuele ruimte voor zowel monoscopische als stereoscopische kijk-condities.

De resultaten laten zien dat het na-effect in laterale richting een magnitude heeft van 20% in de richting tegenovergesteld aan de opzettelijke verplaatsing van de virtuele hand (een negatief na-effect). Tijdens het manipuleren in de VE werd geen invloed gevonden van correspondentie of niet-correspondentie van de virtuele met de echte hand op de prestatie.

Het geobserveerde negatieve na-effect is evidentie voor een low-level parameter aanpassing en niet een high-level strategische aanpassing van de oog-hand coördinatie. Daaruit mag geconcludeerd worden dat bij trainingstoepassingen aangeleerde vaardigheden in VE (ook bij niet corresponderende virtuele hand) overgedragen zullen worden naar de werkelijke wereld.

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This experimental study uses a prism adaptation paradigm to explore visuo-motor adaptation to misaligned virtual hand position. Participants were immersed in an interactive virtual environment with a deliberately misaligned virtual hand position (a lateral shift of 10 cm). We carried out pointing tests with a non-visible hand in the real world before (pre-test) and after (post-test) immersion in the virtual world.
A comparison of pre- and post-tests revealed after-effects of the adaptation of eye-hand coordination in the opposite direction of the lateral shift (negative after-effects). The magnitude of the after-effect was 20% under stereoscopic viewing conditions. However, decreased manipulation performance in VE (speed/accuracy) during the immersion with misaligned hand conditions was not found.
The occurrence of negative after-effects in lateral direction indicates that adaptation is not explained by a strategic change of eye-hand coordination but by a lower-level parameter adjustment. Therefore, acquired visuo-motor skills in VE are likely to transfer to the real world.

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SUMMARY

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TNO Technische Menskunde
Soesterberg

Interactieve Virtual Environments: Aanpassing naar virtuele handpositie

P.J. Werkhoven en J. Groen

SAMENVATTING

Het op directe, natuurlijke wijze met een virtuele hand kunnen manipuleren van virtuele omgevingen maakt geavanceerde toepassingen mogelijk op het gebied van interactief ontwerpen, training, geneeskunde, etc. TNO onderzoekers (Werkhoven & Groen, 1997) hebben aangetoond dat voor grijp- en positioneringstaken het manipuleren met een virtuele hand sneller en nauwkeuriger is dan met traditionele muis/cursor interactie. Echter, de virtuele hand in virtuele omgevingen correspondeert qua positie niet altijd met de echte hand. Dergelijke discrepanties kunnen een adaptatie veroorzaken van de oog-hand coördinatie van gebruikers. Tevens kan het zijn dat de manipulatieprestatie afneemt ten opzichte van een conditie waar de positie van de hand wel klopt.
In deze experimentele studie is een prisma-adaptatie paradigma gebruikt om visuo-motor adaptatie aan niet kloppende virtuele handposities te onderzoeken. Er zijn pre- en post-testen uitgevoerd om de aanwijsprestaties in de werkelijke wereld te meten. Tussen pre-en post-testen werden participanten ondergedompeld in een interactieve virtuele omgeving waarin de virtuele handpositie opzettelijk verschoven was over een afstand van 10 cm ten opzichte van de echte handpositie. Door de resultaten van de pre- en post-test te vergelijken werden mogelijke (negatieve) na-effecten van de adaptatie van de oog-hand coördinatie aan het licht gebracht. Na-effecten werden gemeten in drie verschillende dimensies van de virtuele ruimte voor zowel monoscopische als stereoscopische kijk-condities.
De resultaten laten zien dat het na-effect in laterale richting een magnitude heeft van 20%. Een vermindering van de manipulatieprestatie ten gevolge van een niet-corresponderende virtuele hand in de VE werd niet gevonden.
Een negatief na-effect in de laterale richting suggereert data de adaptatie niet bestaat uit een strategische aanpassing van de oog-hand coördinatie, maar uit een parameter aanpassing op laag niveau. Het is daarom waarschijnlijk dat in VE aangeleerde visuo-motorische vaardigheden overgedragen zullen worden naar de echte wereld.

1 INTRODUCTION

Virtual Environments (VE) are three dimensional computer generated environments offering full immersion and potentially allowing a high level of interaction. Current applications already offer interaction consisting of looking around (head-movements) and navigation (by mouse-like devices). Such interaction is sufficient for the evaluation of cars, ships, buildings or cities in the design phase with respect to sight and lay-out (e.g. Werkhoven, Post & Punte, 1997).
For advanced simulations, however, just looking around is not enough. Applications of VE in the field of training (Loftin & Kennedy, 1995), interactive design, medicine or tele-operation (Park & Sheridan, 1991) require intuitive direct interaction techniques for grasping actions or for controlling instruments.
Direct interaction means virtual hand control. That is, users manipulate their virtual environment through a virtual hand that mimics the movements of their real hand. With this virtual hand, virtual objects can be grasped, rotated or positioned in ways similar to manipulation using the real hand. Such interaction techniques are natural and intuitive and have proven to yield better performance than indirect manipulation techniques through mouse/cursor control. Werkhoven and Groen (1997) compared direct manipulation performance (virtual hand control) with indirect manipulation performance (mouse-cursor control) under both monoscopic and stereoscopic viewing conditions and found that direct manipulation is both faster and more accurate for grasping and positioning tasks.

Direct manipulation performance, however, is expected to rely on the quality of mimicking the real hand. The perceived position of a virtual hand, for example, depends on the properties of the optics of head-mounted displays and also on the accuracy of tracking the position of the real hand. This study deals with the question if users of virtual hands can perceptually adapt to a *discrepant* visual position of the virtual hand, as is often the case in virtual environments, and whether manipulation performance is affected by discrepant hand positions.

1.1 Discrepant virtual hand position

Where is the virtual hand perceived? Position information of our real hand is always provided by our proprioceptive system, mediated by receptors in our muscles and skin. In a VE system, visual feedback of the virtual hand is presented through the head-mounted display (HMD). The visual and proprioceptive information can be discrepant for several reasons. First of all, the settings of the geometrical projection model of the computer can be incorrect. For instance, to obtain correct stereoscopic depth perception, the projection model has to be adjusted to the inter pupillary distance of the user. To save time, this parameter is often set to the population's average, which causes an incorrect perception of depth in most cases. Other causes of mismatches can be visual distortions as caused by the optics of the HMD (Robinett & Rolland, 1992), or distortions caused by the tracking system used to determine the position of eyes and hand. It is fair to say that in low-end VE systems a discrepancy is common.

Another possible cause of non-correspondence between seen and felt virtual hand is the lack of oculo-motor depth cues in virtual environments. In monoscopic displays, accommodation and convergence of the eyes are fixed at a single level, usually at infinity. In stereoscopic displays, the usual coupling between convergence and accommodation is disrupted in order to fuse the two images and benefit from binocular disparity. Mis-accommodation is believed to cause perceptual distortion, although the exact nature of the effect is still unclear (Roscoe, 1991).

1.2 Adaptation

What happens if two sources of information about the same event are discrepant? People usually do not notice discrepancies between seen and felt hand position, which can be shown by letting people wear prisms, which displace the entire visual field to one side. The visually displaced hand is actually felt where it is seen, a phenomenon termed immediate visual capture (Welch & Warren, 1980). The visual sense is known to dominate the other senses.

Experiments in which people wear prisms for longer periods show that eye-hand coordination will make a semi-permanent adaptive change in order to deal with the new relationship between seen and felt hand position. This adaptive change leads to mis-reaching to the opposite side of the prismatic displacement after the prisms have been removed (Helmholtz, 1910). The difference between a pointing task before prism exposure, or pre-test, and the same task directly after prism exposure, or post-test, is called the (negative) after-effect.

Redding and Wallace (1996) theorize that prism adaptation is a remapping between internal representations of visual space and proprioceptive 'limb space'. Limb space is a way to describe the location codes used for open loop directional movements of the limbs. Limb space is mapped to visual space. This enables us to reach for a visual target without having to watch our hands constantly. When the relationship between visual space and limb space is changed, the brain is capable of making a semi-permanent adjustment of the spatial mapping function that links both spaces (Bedford, 1989). This explains the short term negative after-effects when people return to normal conditions.

1.3 Why study adaptation?

There are several reasons why a study of adaptation to virtual hands is important. They are discussed below.

1.3.1 Transfer of learning

One reason to study adaptation to virtual hands is the significance for the learning and transfer of visuo-motor skills. Much is speculated about using virtual environments for learning

purposes, such as surgery (McGovern & Johnston, 1996) or military operations (Smith, 1994). Virtual hands or other body parts could be used to practice visuo-motor skills. Skilled behavior is characterized by open-loop control and replacing visual feedback by proprioceptive feedback (Jordan & Rosenbaum, 1989). According to the theory of motor skills, motor programs are stored in the brain in a general form. At a lower level, parameters are filled in to fine tune the motor program to the needs of the specific situation (Schmidt, 1988).

When the seen virtual hand is in the exact same position as the felt real hand and there is no time delay between hand movement and the corresponding movement of the virtual hand, transfer of learning should be possible, because motor programs will correspond. Unfortunately, time delay and spatial discrepancies are inevitable in current VE systems (Held & Durlach, 1991).

When people can completely adapt to a discrepant virtual hand position, the only difference with a perfectly calibrated situation is the adaptive spatial re-alignment of the brain. Such re-alignment is believed to be obtained by lower level parameter adjustment (Bedford, 1993). This implies that higher level motor programs, achieved during immersion in a virtual environment, are the same as when motor learning would have taken place in a real environment. This is a necessary condition for visuo-motor skills learned in VE to be preserved and successfully applied to real world situations or, vice versa, for skills learned in the real world to be used for operation in a virtual environment.

If no adaptation takes place, the brain has to use a different strategy to solve the discrepancy, which can be referred to as strategic motor control (Redding & Wallace, 1996). In this case, people have to develop specific motor programs for operating in the virtual environment, and transfer of motor skills is not likely.

- Thus, knowledge about the conditions needed for adaptation in VE systems can help evaluate learning environments and make predictions about transfer of motor skills.

1.3.2 Simulation Fidelity

There is another reason why measures of adaptation in VE are useful. Nemire, Jacoby and Ellis (1994) define simulation fidelity as the extent to which responses to changed spatial relationships in the simulated environment resemble responses to analogous changes in the real environment. For instance, a lateral shift of the position of the virtual hand can be interpreted as a simulation of wearing wedge prisms in the real environment. From this point of view, adaptation to discrepant virtual hand position is an indicator of the simulation fidelity of the VE system, more specifically of the virtual hand. At first sight, performance tasks seem to be the most appropriate way to evaluate the display characteristics of the simulation. The problem is that performance is typically influenced by experience and practice. Furthermore, it is often unclear how performance of a certain task generalizes to other domains.

- Adaptation after-effects provide an objective and more general measure for evaluating the simulation fidelity of interactive virtual environments.

1.3.3 Plasticity of the brain

Rolland, Biocca, Barlow & Kancherla (1995) argue that the knowledge about the plasticity of the brain can be useful for manufacturers of VE systems. The limitations of technology will always cause some form of intersensory conflict.

- Knowledge about how people adapt to intersensory discrepancies can guide technology developments.

1.3.4 After-effects

Adaptation leads to after-effects in eye-hand coordination when we return to the real world. In some cases this can be hazardous, for instance when head mounted displays are used by surgeons.

- Knowledge about the persistence of after-effects is needed for defining safety protocols.

1.4 Can we adapt to our virtual hands?

Can people adapt to a virtual hand, as observed through a head mounted display? In current systems virtual space is not as well specified as real space, due to limited field of view, low resolution, slow update rate, lack of valid oculomotor depth cues and, in monoscopic displays, disparity. Furthermore, the computer model of the hand looks different than the real hand, which could prevent people from identifying it with their own hand.
After-effects have been found while the displaced hand was represented by a luminous dot in an otherwise dark room (Welch, 1972). Even if participants were aware that the dot was attached to the experimenter's hand, and not to their own, adaptation after-effects occurred, though somewhat less than when participants were unaware of this. Apparently, adaptation is not much affected by low resolution or people's awareness of the source of visual input from the hand.

Rolland et al. (1995) measured after-effects after seeing the world mediated by video cameras, attached to a low resolution stereoscopic head mounted display. This augmented reality system caused the virtual eye-position to be about 6 cm higher and 16 cm away from the operators' own eyes. This caused their hands to be seen 6 cm lower and 16 cm closer. Small negative after-effects were found in both directions. This is promising for adaptation in computer simulated environments, using similar displays.

1.5 Time delay

Of concern is the considerable time delay between hand and head movements and the rendering of the corresponding image, which characterizes current VE systems. The delay of head movements further degrades the perception of the spatial layout of the virtual environment. The delay of virtual hand movements also raises questions to the possibility of adaptation. Held, Efstathiou and Greene (1966) showed that adaptation to prismatic displacement is totally blocked by time delays of 300 ms. Held and Durlach (1991) found that prism adaptation is heavily reduced when time delays exceed 60 ms, which is not unusual in most VE systems. Given the poor specification of space in combination with time delay, it is not clear if people can adapt to virtual hand position in a current VE system.

1.6 This experiment

The purpose of the present experiment was to explore if the brain makes an adaptive re-alignment of visual and limb space to deal with a discrepancy between real and virtual hand while doing a manipulation task in a current virtual environment system, that is, using a low resolution head mounted display under a time delay of more than 60 ms. The only way to be sure that adaptive re-alignment has taken place is to show negative after-effects in open loop limb positioning (Redding & Wallace, 1996; Welch, 1978). Monoscopic and stereoscopic conditions were compared to see if a stereoscopic image can help adaptive re-alignment.

1.6.1 Subjective calibration of the virtual workspace

Since negative after-effects are found in relation to the discrepancies between seen and felt hand, the nature of the discrepancies inherent to our VE system had to be known first. Theoretically, it should be possible to derive the visual distortion from the physical properties of the VE system used. The problem is that no complete model exists, which takes all aspects contributing to visual position information into account. Furthermore, up to now it is unclear how discrepant depth cues are handled by our perceptual system.

A more convenient way therefore, is to use a subjective method as proposed by Ellis & Nemire (1993), where people subjectively calibrate virtual space by pointing to virtual markers with their unseen hand. In this way a rough linear estimation of the perceptual distortion of virtual space can be made. Mismatches in the depth dimension, that is perpendicular to the screen surface, are expected due to conflicting depth cues as described above and inaccuracies of the head mounted display used. In general, perceiving the depth dimension in displays is more difficult than other dimensions and prone to errors (Zhai & Milgram, 1994).

1.6.2 Lateral shift of the virtual hand

On top of the discrepancies caused by VE system inaccuracies itself (optics and tracking), the virtual hand was shifted 10 cm to the left or right to create an unambiguous difference between seen and felt hand position in the lateral direction. This was done in order to create a possible after-effect big enough to exceed the noise of the measuring technique. A lateral shift allows the results to be linked to the large body of prism adaptation literature which focuses on lateral displacements of the visual field (Kornheiser, 1976; Welch, 1978). It also enables us to compare the simulation fidelity of monoscopic and stereoscopic virtual environments.

1.6.3 Comparison of performance between shifted hand and aligned hand

Mismatches between virtual and real hand position are believed to degrade performance (Ellis, 1991; Rolland et al., 1995). This hypothesis, however, has never really been tested. Good calibration of the virtual hand, that is a good match of virtual and real space, is time consuming and therefore expensive. The manipulation task used for the adaptation experiment was the same as for the manipulation experiment by Werkhoven and Groen (1997), except for the right or left shift of the virtual hand. This makes it possible to compare the performance of a displaced virtual hand with an aligned virtual hand and might shed some light on the benefits of a well-calibrated virtual hand.

2 METHOD

The experiments consist of a pre-test, exposure to a manipulation task, a post-test and a subjective calibration-test.

The pre-test is carried out to get a base-line for the pointing performance to real targets in the real world. The hand was not visible during pointing. Results of the pre-test are compared with the results of the post-test (identical to the pre-test) that is carried out after immersion and manipulation in VE with a deliberately misaligned hand. Differences in the results show how our eye-hand coordination has adapted to the new conditions of the virtual environment (see Figure 1).

To let participants adapt to the virtual environment they carried out manipulation tasks in VE. Participants were instructed to grasp virtual objects (cubes), to rotate them and to place them on a position defined by other cubes.

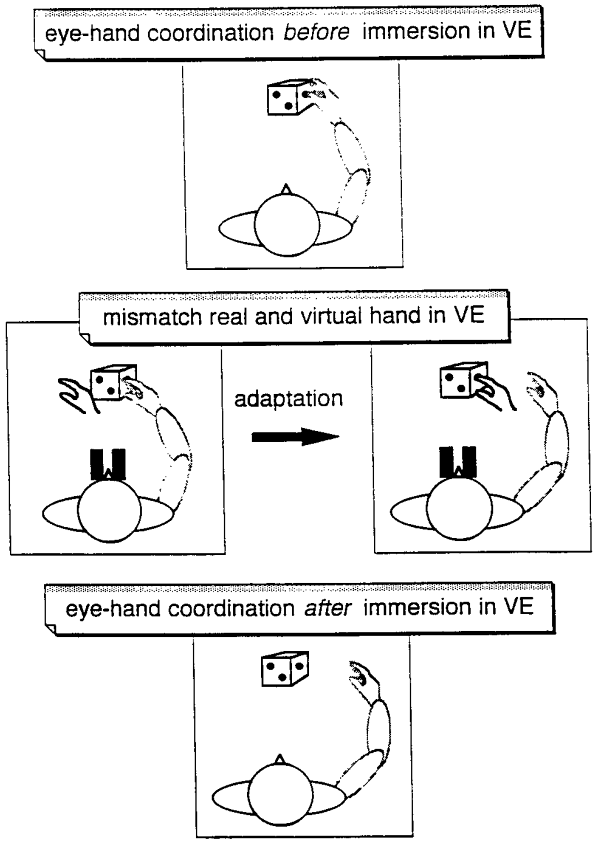

Fig. 1 This sketch illustrates the functions of the pre-test in the real world, the exposure to new conditions in the virtual environment, and the post-test in the real world to reveal adaptation effects (after-effects) of eye-hand coordination.

Finally, a subjective calibration-test (so called by Ellis & Nemire, 1993) was carried out to reveal perceptual deformations inherent to our VE system. Here participants point to the position of virtual objects in VE with their real hand, while both the real and virtual hand are invisible. Ellis suggests comparing the pointing functions in VE (the subjective calibration-test) with functions obtained from pointing at real targets (the pre-test). In this way, subjective errors in open-looped target pointing and systematic errors caused by the pointing technique can be filtered out.

2.1 Participants

Eight right or both-handed students participated in the experiment. Their age ranged from 17 to 27. They all had normal vision, or corrected to normal by contact lenses.

2.2 Apparatus

Image generation. Computer graphics were generated by an Onyx Reality Engine, manufactured by Silicon Graphics. The virtual environment was drawn in normal linear perspective and depth cues such as occlusion and shading were used. The refresh as well as update rate was 60 Hz.

Head-mounted displays. Images were presented by means of the Eyegen 3™, manufactured by Virtual Research Ltd. This head mounted display (HMD) has two color displays with 250×493 pixels. The effective field of view is approximately 40° diagonal, resulting in a resolution of 4.4 arc minutes. Viewing the outside world is blocked by eyecups. The distance between the left and right mini-display of the HMD can be adjusted to fit the user. In stereoscopic conditions, the interocular distance of the projection model was set to 60 mm. In monoscopic conditions, it was set to zero ('Cyclopean vision'). It should be noted that the monoscopic viewing condition was still bi-ocular (not monocular!).

Head tracking. Head position and orientation were tracked using the Fastrak™ (Polhemus), an electromagnetic position and orientation sensing device. It consists of one transmitter and two receivers, one of which was attached to the head mounted display. The transmitter was positioned just above the place where the participants were seated. The range within which tracking accuracy is less than 3 mm error was less than 1 m. The Fastrak and Eyegen 3 are extensively described in Werkhoven and Hoekstra (1994).

Hand tracking. We used a manipulation task described by Werkhoven and Groen (1997) in an immersive virtual environment. For hand tracking the DataGlove™ was used. Position and orientation of the hand were tracked by the second receiver of the Polhemus tracking device, mounted on the back of a DataGlove™ (Fifth Dimension Ltd.) and worn on the right hand. The glove contains fiber optics, and returns for each finger a bending parameter at 120 Hz (Burdea & Coiffet, 1993). The position, orientation and bending parameters were used to render a realistic model of the human hand, which consisted of about 5,000 polygons.

To obtain smooth finger movement, at each cycle, only 20% of the difference between the value of the actual bending of the real and visualized (virtual) finger was added to the new value of the bending of the virtual finger. This caused an additional average delay for finger bending of approximately 70 ms.

A virtual object could be 'grasped', that is attached to the hand, by making contact with both thumb and index finger to the object while keeping the three other fingers closed. It could be released by opening the hand.

For half of the participants, the virtual hand was programmed 10 cm to the left, for the other half it was programmed 10 cm to the right.

Data-collection. The data streams from the data-glove, mouse and position tracker for head and hand were collected and processed by a program running on a 486DX/60 MHz personal computer, and sent to the Onyx. The total delay between movements of the head or hand and

presentation of the corresponding image was approximately 80 ms. A second personal computer controlled the experiment and recorded completion times of the different manipulation tasks and the positions and orientations of the virtual cubes while they were attached to the virtual hand or cursor.

Set-up for pre- and post-tests. For the pre- and post-tests of target pointing, a construction was used inspired on a method used by Held and Gottlieb (1958). It is schematically depicted in Figure 2. It consists of a wooden box (65 × 80 × 65 cm h×w×d) mounted on top of a wheeled table. A flat mirror covered the bottom of the wooden box and a board was attached to an aperture in the frontal side of the box, making an angle of 45° with the horizontal plane. The board contained a small viewing hole, and an indentation for the nose. The inside of the wooden box was illuminated by shining a spotlight through an aperture at the left side of the box. Five wooden cubes with edges of 2 cm could be positioned above the mirror. The cubes were attached to the end of small wooden sticks. The sticks could be pushed back and forth through little holes at the right side of the box in order to adjust the horizontal position of the cubes.

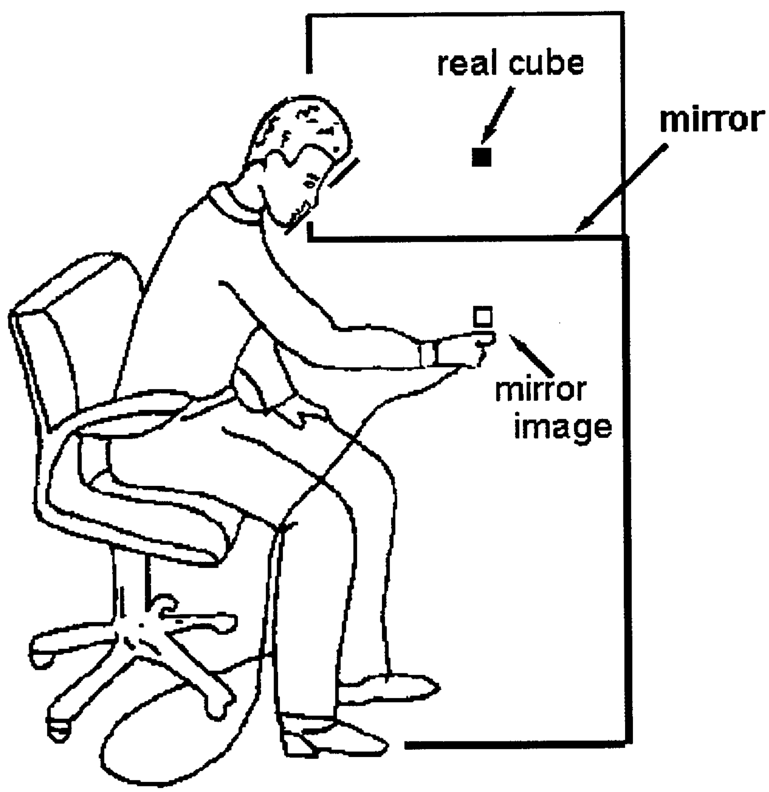

Fig. 2 Schematic drawing of the experimental apparatus used for pre- and post-tests.

The viewing hole offered a view on only the mirror images of the cubes but not on the cubes themselves. The mirror cubes appeared to be within the reaching range of the hand. When

reaching, the view of the hand was obstructed by the mirror. The three dimensional position of the hand was recorded by using the Polhemus sensor. For these target pointing tasks, the sensor was removed from the back of the DataGlove and held between the thumb and index finger.

Subjective calibration. For the subjective calibration of virtual space, the head mounted display could be attached to the wooden box used for the pre- and post-tests, so that it was immobile. When looking through it, the viewing axis made an angle of 45° with the horizontal plane, similar to the view on the mirror. While pointing at virtual cubes, the virtual hand was programmed to be invisible. The total construction could be rolled to the left in order to make way for the adaptation task. A wooden obstruction fixed to the ground enabled the experimenter to reposition the box at exactly the same place in front of the participant for the post-test.

2.3 Stimuli

Workspace. The virtual workspace consisted of a desk surface with telephone and bookshelf, surrounded by walls (see Figure 3). All surfaces were texture mapped. The near side of the desk had a semi-circular indentation, in the middle of which the participant was seated, facing the desk. Participants were seated on a swivel-chair on wheels.

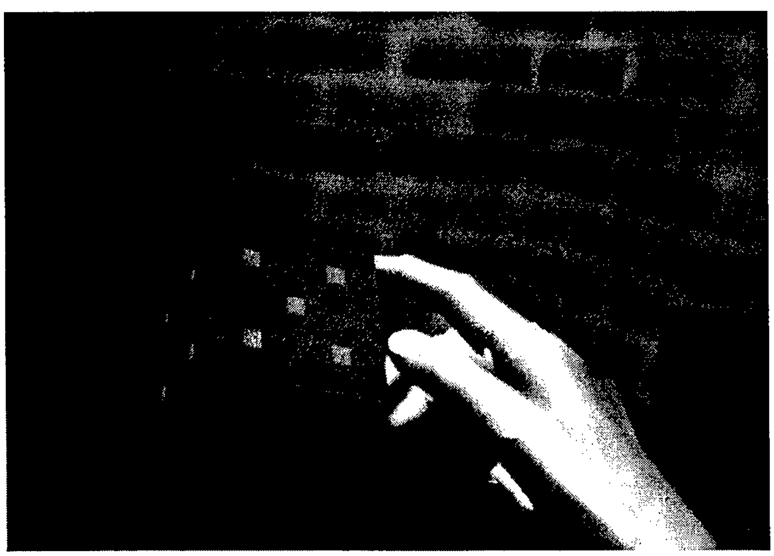

Fig. 3 The virtual work space.

Manipulation. The stimuli for the manipulation task used for adaptation in VE were similar to the task described by Werkhoven and Groen (1997).

For the rotation tasks, participants were asked to grasp a die presented on the desk at the right-hand side. The size of the die was 10 cm.

For the positioning task three cubes were positioned above the desk surface. They served as three corners of an imaginary square (defined by the centers of the three cubes), which could be either parallel to the desk (in the horizontal plane) or parallel to the frontal plane. Participants were asked to position the die (size 10 cm) on the fourth (missing) corner. The configuration of these cubes also varied over trials. For both orientations of the square (in horizontal or frontal plane), each of the four possible corners could be the missing one. The edge size of the cubes constituting the square was 10 cm. Distances between these cubes were 50 cm. The 8 possible configurations (four corner positions, two orientations of the square) were presented once in random order for each combination of viewing (mono/stereo) and manipulation (direct/indirect) condition tested. The center of the square was randomly assigned to one of seven possible locations: one was the basic location, 40 cm above the desk, 50 cm away from the observer, and shifted 20 cm to the left. The other six could be calculated by adding or subtracting 5 cm along one of the three axes.

Pre- and post-tests. For the target pointing tests in the real world (pre- and post-tests), wooden cubes at seven different target positions were presented five times each in random order. Three cubes were at the viewing axis at distances of 33, 43 and 53 cm from the viewing hole. Two cubes were positioned 10 cm perpendicular below and above the center of the three cubes at the viewing axis and two cubes 12.5 cm left and right of the center cube (at the horizontal axis).

Subjective calibration. For the calibration of virtual space, seven virtual cubes with 5 cm edges were presented five times in random order. The coordinates of the virtual cubes relative to the eye were the same as those used for the real cubes in the pre- and post-tests, except for the three cubes along the horizontal axis. Their original positions were not visible within the limited field of view of the head-mounted display used. Therefore, they were moved 7 cm further along the viewing axis, and 7 cm downward along the vertical axis so that they became visible. Judgments were only done with stereoscopic vision because under monoscopic conditions a lack of disparity in the now stationary head mounted display provided insufficient depth information to judge the distance with reasonable confidence.

2.4 Design

A within-participants design was used with four conditions that were combinations of the manipulation condition (left- or rightward lateral displacement of the virtual hand) and viewing condition (stereoscopic or monoscopic). The order of conditions was balanced (see Table I). The dependent variable was the negative after-effect along the horizontal, vertical and viewing axis. The negative after-effect is defined by the difference between hand position in pre- and post-test, in the opposite direction of the visual displacement of the hand. In each group, the order of conditions was balanced (see Table I).

Adaptation was tested for each participant for each viewing condition (mono and stereo) and a single displacement (left or right). The adaptation session consisted of 35 positioning trials. Table I shows the sequence of sessions for each participant (SL=stereo/left shift, ML= mono/left shift, SR=stereo/right shift, MR=mono/right shift).

Table I Experimental design.

participant		1st adaptation session				2nd adaptation session			
1	**PRE-TEST**	SL	**POST-TEST**	**2 HR BREAK**	**PRE-TEST**	ML	**POST-TEST**	**15 MIN BREAK**	**CALIBRATION**
2		SR				MR			
3		ML				SL			
4		MR				SR			
5		SL				ML			
6		SR				MR			
7		ML				SL			
8		MR				SR			

SL: stereo, left shift; SR: stereo, right shift
ML: mono, left shift; MR: mono, right shift

2.5 Procedure

General. Participants read instructions about the working of the VE system. They were told that their eye-hand coordination was tested before and after the adaptation phase (immersion in VE). They were seated on a desk chair in front of the wooden box looking through the viewing hole. During pre- and post-test, participants wore the DataGlove. This was done to assure that after-effects could not be due to adaptation to the weight of the DataGlove.

Pre-test. The pre-test went as follows. The position sensor was held between thumb and index finger. The five cubes were at the left most side of the box. The experimenter placed a cube at one of the target positions by pushing the wooden stick forward. Following this, participants placed the position sensor to coincide with the mirror image of the cube and gave a verbal sign when finished. No time limit was given. The experimenter recorded the sensor position by pressing a key. After this, participants withdrew their hand and the cube was pushed back to its initial position. In this way, all 35 positions were tested.

Manipulation task. After the pre-test the wooden box was moved away and the position sensor was mounted on the glove. Participants did a manipulation task in the virtual environment, under stereoscopic as well as monoscopic conditions. The manipulation tasks were similar to the tasks used by Werkhoven and Groen (1997).

At the beginning of the trial, a die was presented on the desk on either the left-hand or the right-hand side of the participant. When an audible tone sounded, they grasped the die. When the die was presented on the *left-hand side,* participants were asked to position the die on the missing corner of an imaginary square formed by the middle points of the cubes (see Stimuli). The orientation of the die had to match the orientation of the other cubes (the edges aligned with the coordinate axes of the VE).

When the die was presented on the *right-hand side* participants had to rotate the cube following a specific sequence. After they had grasped it, they pitched it 90° until number one was on top. When the surface containing the number one made an angle with the ground plane of less then 10°, a second tone confirmed that the pitch was successful. After this tone, the dice had to be rolled 90° to the left until number one was on the left side of the die and perpendicular to the sagittal plane. Again a difference of 10° was allowed. After completion a second tone sounded, and the die could be released. Participants were instructed to grasp and rotate the dice as fast as possible.

There were no practice trials. The grasping and releasing of cubes was demonstrated by the experimenter.

Post-test. Immediately after the last trial, participants were asked to close their eyes. This was to prevent quick decay of adaptation when viewing the real, undistorted hand. The table containing the wooden box was moved in place. The experimenter removed the head mounted display and handed the position sensor to the participant. After the participants opened their eyes, the experimenter started the post-test, which was identical to the pre-test.

Second condition. Two hours after finishing the first post-test participants were tested a second time under the other viewing condition following the same sequence of pre-test, adaptation and post-test.

Subjective calibration test. Fifteen minutes after the second post-test, the calibration test was done. Participants looked through the head mounted display, which was now fixed to make an angle of 45° with the horizontal plane. This time 35 virtual cubes were presented one by one. Participants were asked to position the position sensor on the place were they saw the virtual cube. They verbally reported when they were ready. The cube disappeared after the experimenter recorded the sensor coordinates. After the hand was withdrawn, the next cube was presented.

2.6 Analysis

The positioning results are measured along axes that were aligned with the virtual desk. However, for the analysis of the results of the pre-, post- and subjective calibration tests we wanted to express the positioning results along dimensions relative to the (fixed) viewing direction of the participants. That is, the axis along the viewing direction (called depth), the horizontal axis orthogonal to the viewing direction and the axis orthogonal to horizontal and

depth axis (the new vertical axis). Basically this new coordinate system is the old system rotated about the horizontal axis such that the old depth axis was aligned with the viewing direction (the new depth axis).

3 RESULTS

For each target cube, real and virtual, the mean coordinate of five pointing trials was calculated for each position, condition and participant. When the standard deviation of the five pointing results exceeded three cm, the value deviating the most from the median was considered an outlier.

3.1 Subjective calibration

To get an impression of the perceptual distortion of virtual space, the average position of the virtual cubes pointed to by participants was plotted against the position used by the projection model of the computer for each dimension (horizontal, vertical and depth). A linear regression line was fitted. This was done separately for each dimension. The slope of the line reflects a first order linear scaling of virtual space. When no distortion is present, the expected value is one. A larger or smaller slope corresponds to magnifications or minifications. The intercept is expected to be zero cm. Non-zero values of the intercept indicate a constant shift of the visual space perceived. Note that the subjective calibration test was carried out under stereoscopic viewing conditions only.

Regression results for the subjective calibration tests (and other tests) are shown in Table II. A slope value marked with an asterisk indicates that this slope value differs significantly from one ($p<0.05$). An asterisk marking an intercept value indicates that this intercept value differs significantly from zero ($p<0.05$).

Depth dimension. The line labeled 'calibration' in Figure 4 is the regression function for pointing results along the viewing axis (depth). The regression function is described by a slope of 0.55 and an intercept value of 3.02 cm with a squared correlation coefficient $\rho^2=0.86$. Obviously, perceptual deformation occurs because the regression coefficient deviates significantly from one. To distinguish open-loop pointing errors from perceptual distortions in VE we will compare this regression line with pointing results in the real world (the pre-test) in the next section.

Horizontal dimension. The regression line in the horizontal dimension for the subjective calibration test (virtual targets) had a slope of 0.85 and an intercept value of -3.0 cm with a squared correlation coefficient $\rho^2=0.99$.The slope and intercept values do not reflect a perfectly calibrated situation and differ significantly from one and zero, respectively.

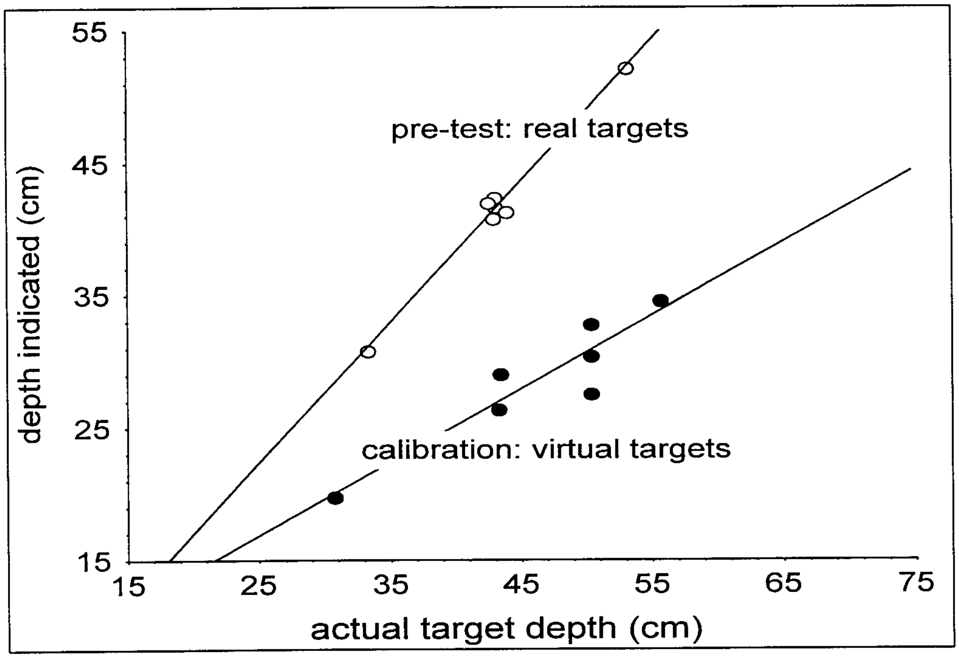

Fig. 4 Results of the subjective calibration test and pre-test for the depth dimension (the distance along the viewing direction). The depth of targets indicated by participants is plotted vertically against the actual positions of real targets (pre-test) or virtual targets (subjective calibration test). The point between the eyes was taken as the origin. Viewing conditions were stereoscopic.

Vertical dimension. In the vertical dimension regression lines for the subjective calibration test had a slope of 0.95 and an intercept of −0.57 cm with a squared correlation coefficient $\rho^2 = 0.99$. The deviations of slope and intercept from what we expect in perfectly calibrated situations are not significant.

3.2 Pre-tests and a comparison with the subjective calibration results

This section shows the results of the pre-tests in which participants pointed to real targets before immersion in VE. To facilitate a direct comparison with the results of the post-tests under stereo conditions, we have chosen to present only the pre-tests that preceded immersion under stereo conditions. Nevertheless, the results of pre-tests are expected to be independent of the viewing condition (mono/stereo) during immersion in VE. Indeed no significant differences have been observed between pre-tests preceding mono and stereo conditions.

To facilitate a comparison of subjective calibration, pre- and post-tests, regression results (slopes, intercepts and squared correlation coefficients) for all tests are given in Table II.

Table II Regression results for subjective calibration, pre- and post-tests (stereo-conditions only).

Dimension	Subjective calibration			Pre-test			Post-test		
	S	I	ρ^2	S	I	ρ^2	S	I	ρ^2
horizontal	0.85*	-3.00*	0.99	0.93*	-3.10*	1.00	L: 0.97	-0.88*	1.00
							R: 1.02	-6.45*	1.00
depth	0.55*	3.02	0.86	1.07	-4.29	0.98	1.10	-1.58	0.98
vertical	0.95	-0.57	0.99	0.86*	-1.88*	1.00	0.93*	-0.57*	1.00

S: slope; I: intercept; ρ^2: squared correlation coefficient;
L: left virtual hand displacement; R: right virtual hand displacement;
A slope value marked with an asterisk indicates that this slope value differs significantly from one ($p<0.05$).
An asterisk marking an intercept value indicates that this intercept value differs significantly from zero ($p<0.05$).

Depth. Figure 4 shows the regression line (labeled 'pre-test') for the positions indicated along the viewing direction (depth) versus the actual position of the (real) targets during those pre-tests preceding stereo conditions. This regression line has a slope of 1.07 and an intercept value of -4.29 cm with a squared correlation coefficient $\rho^2=0.98$. The slope of this regression line does not differ significantly from the value 1 suggesting that open-loop target pointing errors are not significant. Therefore, the significant difference between the slopes of the pre-test and subjective calibration lines [$t(10)=4.15$, $p<0.005$] can only be explained by the perceptual distortion of the virtual environment. The significantly smaller slope in VE suggests an underestimation of depth of almost 50% in VE.

Horizontal dimension. For the horizontal dimension, the regression line for the pre-test (real targets) was described by a slope of 0.93 and an intercept of -3.1 cm with a squared correlation coefficient $\rho^2=1.00$.
The difference between the slopes of the regression lines of the pre-test and the subjective calibration test in the horizontal dimension was not significant [$t(10)=2.02$, $p>0.05$]. Both intercepts were significantly smaller than zero, $t(5)=19.01$ and $t(5)=14.64$, respectively, $p<0.001$. This indicates a systematic tendency to point too far to the left with a constant factor. Because both the virtual and real world show the same effect, it can be excluded that this effect is caused by significant distortion of the VE system in the horizontal dimension.

Vertical dimension. In the vertical dimension regression lines of the pre-test had a slope of 0.86 and an intercept value of -1.81 cm with a squared correlation coefficient $\rho^2=1.00$. These regression lines reflect possible open-loop pointing errors. Differences between pre-test (real targets) and subjective calibration results (virtual targets) reflect distortions of virtual space. Only the difference between the intercepts (not between the slopes) for pre and subjective calibration tests was significant [$t(10)=3.43$, $p<0.01$] indicating that participants pointed above the target positions in virtual space. Target height appears to be visually overestimated.

3.3 Combining pre- and post-tests: the after-effect

For each target position the after-effect was determined by taking the difference between the post- and pre-test. In the lateral direction, this difference was signed positive when it was in the opposite direction of the displacement of the virtual hand. The mean after-effects in mono- and stereoscopic conditions are shown in Figure 5.

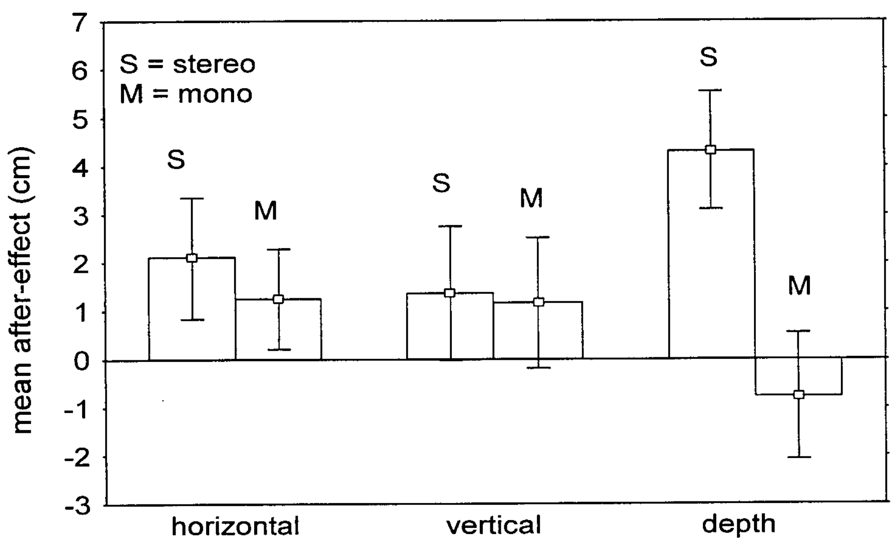

Fig. 5 Mean after-effects under stereoscopic and monoscopic conditions for each dimension. The whiskers indicate a magnitude that equals 1.96 times the standard error. When the whiskers do not touch the zero base-line, the mean after-effects differ significantly from zero ($p<0.05$).

The after-effects in the *vertical* dimension did not differ significantly from zero.

The after-effect in the *horizontal* (lateral) dimension differed significantly form zero by 95% confidence intervals. The difference between monoscopic and stereoscopic immersion was not significant [$t(7)=1.35$, $p=0.22$]. After-effects along the horizontal dimension are most likely to be caused by the lateral displacement of the virtual hand. People compensate for a virtual hand that is continuously perceived left of the real hand position by adapting their eye-hand coordination. This compensation remains active after returning to the real world for the time that their real hand is invisible. The after-effect is systematically in the opposite direction of the lateral displacement and is about 20% of the magnitude of the lateral displacement. Figure 6 shows the lateral after-effects for different target positions. Interestingly, participants pointed 2 cm left of the target positions during the pre-test. This must have been due to open-loop pointing error. During the post-test after a lateral shift to the left during immersion, the after-effect resulted in a shift of about 2 cm on average to the right. When the post-test was carried out after immersion with a lateral shift to the right, the pointed positions during the post-test were about 2 cm to the left of the pre-test positions.

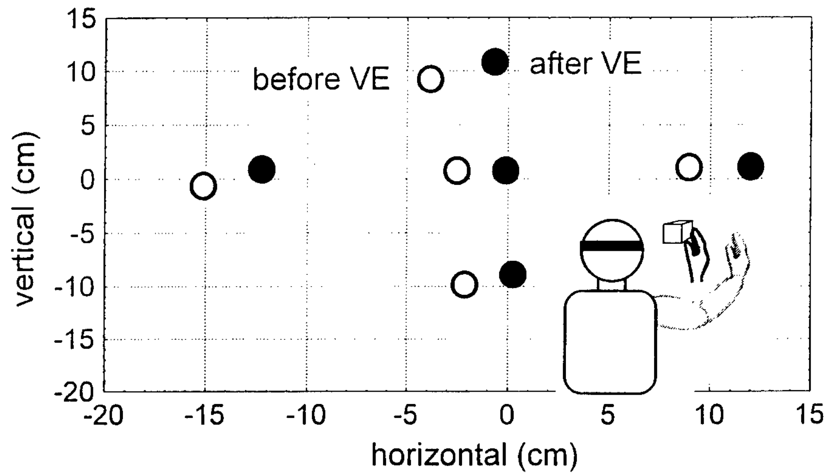

Fig. 6 Lateral after-effects (along the horizontal dimension) for different target positions. Targets are shown as projections in the frontal plane (orthogonal to the viewing direction). Filled symbols indicate the positions pointed to during the pre-test. Open symbols show the pointed positions during the post-tests. The difference in positions of a target between pre- and post-test (caused by immersion in VE) is called the after-effect.

In the *depth* dimension, after-effects in the stereoscopic condition were significantly larger than those in the monoscopic condition [$t(7)=4.91$, $p<0.05$]. It was only in the stereoscopic condition, that the after-effect (4.3 cm) differed significantly from zero by 95% confidence intervals. This after-effect shows that during the post-test participants pointed to positions behind the actual position of the real targets. This might have been due to exposure to a virtual world in which the virtual hand was visually perceived closer to the body than the actual real hand position. For example, Figure 4 shows a perceptual underestimation of target position in VE of (subjective calibration versus pre-test) of 14 cm at a target distance of 45 cm. Participants therefore, had to position their real hand behind a virtual target in order to touch the target with their virtual hand. As a consequence, after returning to the real world, participants kept pointing behind the actual position of real targets when their hand was invisible. In conclusion, the after-effect in the depth dimension is consistent with the underestimation of depth in the virtual world as shown in the subjective calibration experiment.

3.4 The dependency of after-effects on target depth

The subjective calibration experiment clearly showed that the perceived distance (in depth) of targets in virtual space is systematically underestimated. In fact, the linear relation between indicated positions in virtual space and actual positions has a regression coefficient of 0.55. This suggests that the perceived virtual space is scaled or minified with respect to the geometric world it represents. If we hypothesize that after-effects are caused by perceptual deforma-

tions of virtual space, it is interesting to check how the after-effects observed depend on target depth. Does the after-effect scale with target depth or is it constant?

For this purpose we have plotted the after-effect as a function of target depth (see Figure 7). The regression lines are also shown in Figure 7. The regression line for the pre-test has a slope of 1.07 and an intercept of -4.29 cm ($r^2=0.98$). For the post-test we find a regression line with a slope of 1.10 and an intercept of -1.58 cm ($r^2=0.98$).

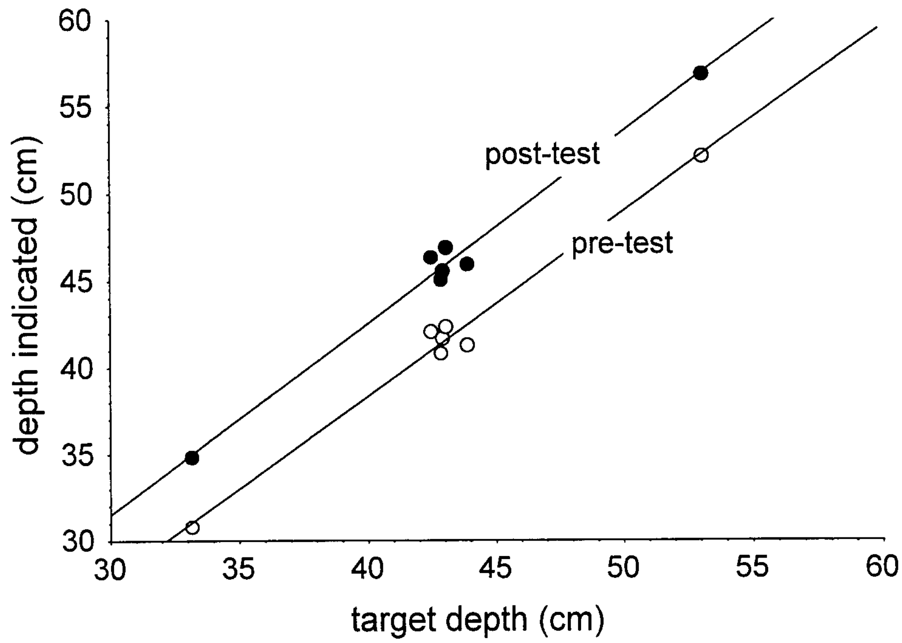

Fig. 7 Indicated (pointed) target distances along the viewing axis (depth) plotted against the actual distance of the real targets for both pre- and post-tests. Only those pre- and post-tests preceding and following stereo exposures to VE are included.

The slopes of the regression lines of pre- and post-test do not significantly differ [$t(10)=0.44$, $p>0.5$], although the slope of the pre-test is slightly larger. The intercepts did not differ significantly either [$t(10)=0.77$, $p<0.5$]. The magnitude of the after-effect is 4.3 cm on average. Due to the small after-effect and the limited range of target positions tested it is hard to distinguish a shift of regression lines from a scaling effect. We carried out an ANOVA analysis (within subjects) with two independent variables. The first variable was the type of test (pre-test versus post-test) and the second was the target distance (33.1 versus 55.2 cm from the eye). A significant interaction effect would indicate a difference between slopes of pre- and post-test.

The non-significant interaction effect found ($p=0.13$) suggests that the regression lines are shifted and thus that adaption does not scale with target depth but is constant.

To further reveal some characteristics of the adaptation process we have studied the dependency between magnitudes of lateral after-effects and after-effects in depth. If a single process would generate both types of after-effects, the magnitudes of both effects are expected to co-vary within a subject (large magnitudes along both axes for sensitive participants, small magnitudes for insensitive participants).
We have, therefore, correlated the individual magnitudes along the two axes (horizontal and depth) under stereo conditions. Pearson's r was 0.02. This zero correlation effect suggests that the adaptation in depth and the adaptation along the horizontal axes are caused by independent processes.

3.5 The effect of a displaced virtual hand on manipulation performance

In this section we check whether the displacement of the virtual hand influences manipulation performances as reflected in time it takes to grasp, pitch, roll and position the dice and the accuracy of positioning are influenced by displacing the virtual hand. In Werkhoven and Groen (1997) these performance indicators were measured for identical tasks, but with a virtual hand that was not laterally displaced as in our current experiments.
In order to be able to compare the results of the present experiment with the results of Werkhoven and Groen (1997) it was necessary to consider only the trials that were carried out under identical conditions in both experiments. Grasping and rotation completion times of both experiments were therefore included only when the die had a size of 10 cm and when it was initially presented on the right-hand side of the participants. The grasping times for the positioning task of the present experiment were not taken into the analysis because these grasping times included the time taken by participants to explore the position of the imaginary target square. Further, for grasping and rotating, the first eight trials in the present experiment were considered practice trials and not taken into the analysis.

Positioning errors. The positioning error is defined as the Euclidean distance between the indicated position and the target position. Separate t-tests for comparing the means of positioning errors between conditions with and without a laterally displaced virtual hand revealed no significant differences in positioning errors. For the group with a shifted virtual hand, the mean positioning error was 7.6 cm in the stereo condition and 11.1 in the mono condition. For the group with an aligned virtual hand this was 8.9 cm and 13.9 cm, respectively, the difference not being significant [$t(10)=.85$, $p>0.40$ and $t(10)=1.65$, $p>0.10$, respectively].

Completion times. We also compared the completion times of manipulation actions such as grasp, pitch, roll and positioning between the groups with aligned and with shifted virtual hands (Figure 8). Again, grasping times are considered for the rotation tasks only, not for positioning tasks.

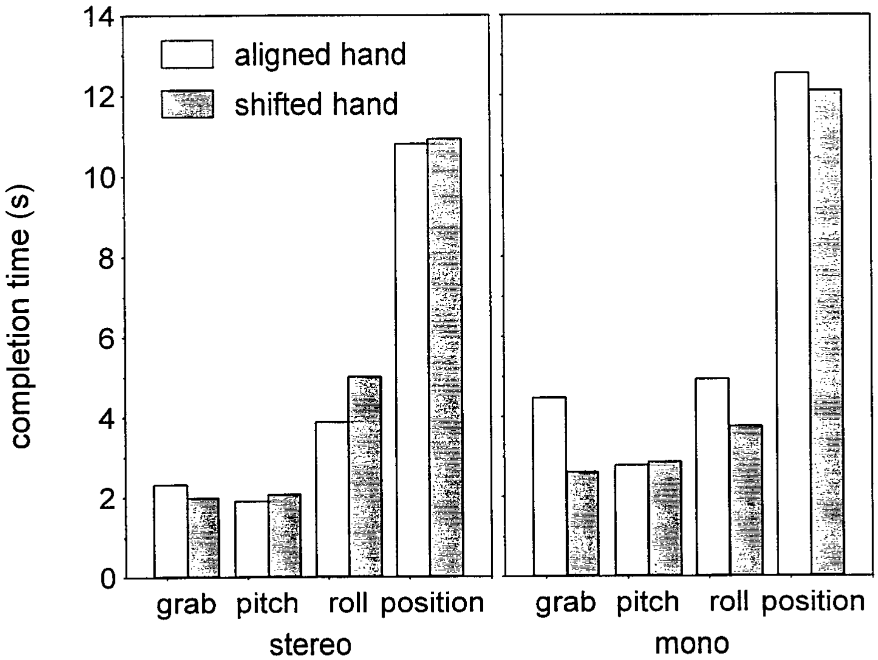

Fig. 8 Mean completion times of grasping, pitching and rolling tasks for the group with an aligned virtual hand and the group with a laterally shifted virtual hand, in both stereoscopic and monoscopic conditions.

No significant differences between aligned and non-aligned conditions were found. It should be noted that positioning completion times of the present experiment include the time needed to lift the cube which may take longer compared to the previous manipulation experiments (Werkhoven & Groen, 1997) where the cube was already 'in the air' when positioning started. The completion times needed for positioning only (not lifting) may therefore even be a little shorter for the present experiment (shifted virtual hand conditions) than for the previous experiment (aligned virtual hand).

4 GENERAL DISCUSSION

4.1 Perceptual deformations of virtual space in our VE system

Perceptual deformations were revealed by the subjective calibration test after correction for the open-loop pointing errors as measured in the pre-test. Therefore, slopes and intercepts of regression lines of calibration and pre-test were compared.

Horizontal dimension

A comparison of the subjective calibration test and the pre-test revealed no significant perceptual distortion of virtual space along the horizontal dimension. Our data suggest, however, that there might be a slight but systematic minification in the lateral direction. Combining this with the programmed shift of 10 virtual cm, we can conclude that in the horizontal dimension, the hand was perceived maximally 10 cm to the right or to the left.

Depth (viewing axis)

Distances along the viewing axis were perceived closer by a scale factor of almost 50%, that is, when disparity was present. Under-estimations of depth are not exclusively explained by low-quality HMD optics or disparity problems. An alternative explanation is in terms of monoscopic cues that are incorrectly interpreted. For example, the distance of a cube can be estimated from its projected retinal size when its objective size is known. We call this the size cue. Werkhoven and Groen (1997) found that the retinal size of virtual objects was a strong distance cue when the layout of visual space was ambiguous, in particular under monoscopic conditions and when head-movements are restricted such that motion parallax cues were ineffective. However, also under stereoscopic conditions and in the presence of motion parallax cues, effects of size cues were observed. When objective knowledge about the actual cube size is not available and the size is estimated incorrectly the perceived distance of the cube may be affected. For example, when the objective size of the virtual cubes is estimated twice as small as the objective size, the cube may appear twice as near. Relying on such size cues effectively scales the range of perceived distances of the virtual targets (cubes) used in the subjective calibration tests. Of course, one may wonder why the objective size of the target cubes was systematically under-estimated (they appeared closer than they were) and not over-estimated.

Vertical dimension

A comparison of pre-test and subjective calibration results for the vertical dimension has shown a slight but systematic over-estimation of height in virtual space of about 1 cm. Consequently, the height of the virtual hand will be perceived above the real hand position. In the next paragraph, where we compare post- and pre-tests, we will discuss this observation in relation to the after-effects found.

4.2 After-effects

4.2.1 Horizontal dimension

A small but reliable after-effect was found in the opposite direction of the displacement of the virtual hand. The average effect amounted to 20% of the theoretical maximum of 10 cm. Data

suggests that this was less in the monoscopic condition, the difference being not significant, however. The direction of the after-effects found for different targets correlated perfectly with the directions of the intentional shifts (left/right randomized) indicating that the lateral shifts have indeed caused the after-effects.

What to expect based on literature? The 20% negative after-effect corresponds to the percentage found by Held and Durlach (1991) under a delay of 60 ms between hand movements and visual feedback. In their experiment, the hand was represented by a luminous dot. In prism-adaptation experiments, after-effects for relatively short exposure periods normally never exceed 70% (Welch, 1978). It is possible that the magnitude of the after-effect found in the present study was negatively influenced by a number of factors. In the period between immersion in the virtual environment and the post-test spontaneous decay of adaptation might have taken place. Adaptation after-effects disappear when information about the real hand position is present (Welch, 1978). When the experimenter prepared the post-test and handed the position sensor, proprioceptive and auditive spatial information about the hand might have started the decay process. Furthermore, after-effects are found to decrease as the situation of exposure to sensory discordance and post-test are less resembling. For instance, in a prism adaptation experiment, Ulharik and Canon (1970) found a smaller effect when the prism goggles were removed than when goggles without prisms were worn during pre- and post-test. In the present study, the situations of exposure and both pre- and post-test differed in a great number of aspects.

Where does adaptation take place? It is not clear from this study what the locus of adaptation was. Adaptation can involve a proprioceptive shift, (a recalibration of felt limb position) or a visual shift (a recalibration of visual perception) or a combination of both. This experiment measured the total shift. Welch (1978) states that the least attended modality is more likely to recalibrate. In the present exposure task, visual information was surely the most important. It is therefore likely that the proprioceptive shift was the main contributor to the negative after-effect.

4.2.2 Depth dimension

A strong after-effect of more than 4.0 cm was found in the depth dimension. Apparently, under the stereoscopic condition, depth was sufficiently well-specified to invoke adaptation in the depth dimension. Participants adapted their eye-hand coordination to a new condition in the virtual environment under which the virtual hand was perceived closer than the real hand. To solve this inconsistency, they learned to rely on the visually perceived position of the virtual hand for manipulation purposes and ignore the proprioceptively perceived real hand position. This adaptation effect lasted even after returning in the real world.

Disparity and accommodation. The positions pointed to with the real hand during the post-tests were systematically further away than the actual target position. This suggests that during the adaptation phase in the virtual world the distance of targets and of the virtual hand were

under-estimated relative to the geometric world that was represented. The absence of an after-effect in the monoscopic condition suggests that depth cues as convergence and disparity are involved in the recalibration of eye-hand coordination. Accommodation was fixed in both conditions and could not possibly have been adapted.

Eye muscle potentiation. A completely different explanation for the difference in pointing performance between pre- and post-test is the possible occurrence of eye muscle potentiation. After prolonged efferent signals, muscles show a reflexive contraction for a period after the efferent signal has stopped. This effect has been demonstrated for eye muscles after sustained convergence and found to influence distance perception (Paap & Ebenholtz, 1977). The decoupling between accommodation and convergence while looking at displays could have caused abnormal efferent signals to diverge or converge the eyes. Returning to the real world, a divergence may have persisted possibly causing an over-estimation of distance. As a result participants would point behind the target during post-test. Thus, eye muscle potentiation is a possible explanation alternative to the adaptive re-alignment hypothesis for the observed after-effects in depth (not for the other dimensions!).

Have other researchers found unique evidence for eye muscle potentiation or adaptive re-alignment in the depth dimension? Rolland et al. (1995) recently studied adaptation effects and shifted the virtual hand across a distance of 16.5 cm along the viewing axis towards the participants. They observed after-effects with a magnitude of 4 cm which corresponds nicely with the magnitude of the after-effect observed in our experiment. Has Rolland's after-effect been caused by adaptive re-alignment? Perhaps yes. However, in that case we have to assume a psychological limit of adaptation (saturation) because we notice similar after-effects (4cm) for Rolland's as well as our experiments for different discrepant positions of the virtual hand in depth. Alternatively, however, their after-effect is also, at least in part, caused by the prolonged use of a stereoscopic HMD (e.g. eye-muscle potentiation).

To test the eye muscle potentiation hypothesis in our experiments, we have informally tested participants before and after immersion in a 'handless' virtual environment, where they did the same task using mouse-cursor control. First results indeed show similar pointing errors as observed in our adaptation experiments which supports the eye-muscle potentiation hypothesis for the depth dimension.

Independent processes. A zero correlation was found between after-effects in the horizontal and those in the depth dimension. This indicates that after-effects in the two directions are mutually independent. We hypothesize that the after-effects in the lateral horizontal directions have been caused by a recalibration of the eye-hand coordination (adaptation) whereas the after-effects in depth have been caused by continuing abnormal efferent signals after immersion (eye-muscle potentiation). In our case, a visual calibration could mean a recalibration between disparity or convergence or both and the perceived distance. Such recalibration of disparity and perceived distance has been found in the past (Wallach et al., 1963). Further, Wallach and Smith (1972) found a visual recalibration as well as a proprioceptive recalibra-

tion of eye-hand coordination after exposure to a condition where convergence conflicted with accommodation and felt hand position.

Plasticity. It is remarkable that the difference in pointing performance between pre- and post-tests in the depth dimension involved a constant shift, rather than a scale factor. Given the perceptual distortion (a depth compression of almost 50%) as revealed by the subjective calibration tests, a scale factor between one and two was expected to describe the relation between real and judged distance during the post-tests.
If eye muscle potentiation is the right explanation, one may ask why eye muscle potentiation results in a shift of the perceived virtual space rather than in a scaling.
If recalibration of eye-hand coordination is the right explanation, one may wonder why the brain is not capable of recalibrations other than shifts of virtual space. It is not clear from the literature which spatial mapping functions comprise the plasticity of the brain. There is evidence that only linear functions can be used (Bedford, 1993). Clearly, conclusions about the present finding of changes in distance perception have to be drawn carefully. Further research is needed to reveal the exact nature of the observed after-effects.

4.2.3 Vertical dimension

The comparison of post- and pre-tests along the vertical dimension revealed an insignificant but systematic after-effect in both monoscopic and stereoscopic conditions. Participants pointed about 1 cm higher in the post-test after immersion in VE than in the pre-test before immersion.
This after-effect cannot be a result of an adaptation of the eye-hand coordination to a VE immersion in which the virtual hand was systematically perceived *beneath* the real hand. This has been proven by comparing the results of subjective calibration and pre-tests indicating that the virtual hand was perceived *above* the real hand. Thus, we should call this after-effect a *positive* after-effect in contrast to the negative after-effects found in other dimensions.

Rolland et al. (1995) also studied adaptation effects after immersion in an augmented reality system. In their experiments head-mounted cameras were positioned above the eyes. Consequently the hand was perceived 6.2 cm beneath the real hand position. They observed an after-effect with a magnitude of 1 cm in the opposite direction of the vertical displacement of the perceived hand and called this a negative after-effect.
First, from their article, it is not clear whether this after-effect was significantly different from zero. Second, if it is significant, it is not evident that the vertical after-effect is caused by the vertical displacement of the perceived ion during immersion. We say this because we found a *similar* after-effect after immersion with a virtual hand that was perceived 1 cm *above* the real hand position instead of 6.2 cm *beneath* the real hand position as in Rolland's experiments. So it seems that the same after-effect can be obtained with opposite displacements of the perceived hand suggesting that an explanation in terms of adaptation of the visuo-motor pathway is not likely.

4.3 Simulation fidelity

After-effects in lateral direction are a measure of the simulation fidelity. We found significant after-effects under stereoscopic conditions, but not under monoscopic conditions. One may therefore say that the simulation fidelity decreases under monoscopic conditions.

The occurrence of negative after-effects in the lateral direction under stereoscopic conditions shows lower level parameter adjustment in eye-hand coordination (Redding & Wallace, 1996). This is promising for those interested in using virtual hands to acquire visuo-motor skills. Skilled behavior is characterized by open-loop control and replacing visual feedback by proprioceptive feedback. According to the theory of motor skills, motor programs are stored in the brain in a general form. At a lower level, parameters are filled in to fine tune the motor program to the needs of the specific situation (Welch, 1978). Because adaptation appears to take place at a low level and their after-effects are found, it is likely that the motor skill strategy at a higher level is not affected and can be transferred to real world situations. Further research should point out the limits of the spatial and temporal discrepancies in VE systems allowing a transfer of visuo-motor learning. Adaptation to discrepant visual information from the fingers also has to be studied in this context.

4.4 Comparison between non-aligned and aligned virtual hand control

The data from the present manipulation performance task with discrepant lateral virtual hand positions did not reveal any decline in speed or accuracy in the present experiment compared to the data obtained by Werkhoven and Groen (1997) for aligned virtual hand control. For the tasks used, which are typical grasping, rotating and positioning tasks with small objects, a lateral difference of 10 cm does not seem to influence performance.

Rolland et al. (1995) found a decrease in a manual pegboard task, when hand position was shifted vertically and in depth, compared to performance on the same task in the real world. They attribute this performance decrease to the intersensory conflict (mis-alignment), although they admit that the poor HMD resolution might play a role (estimated to be 8 arcmin, see Edwards, Rolland & Keller, 1993). Our experiments showed that a discrepancy between perceived and real hand position did not measurably decrease manipulation performance compared to aligned conditions though both conditions were tested in the virtual world using a HMD with a resolution of 4.4 arcmin. Thus, our findings suggest that the decrease compared to the real world found by Rolland et al. is not likely to be caused by mis-alignments of the virtual hand but rather by low HMD resolution, perhaps combined with the absence of oculomotor cues.

One can not exclude, however, that manipulation performance is similar in laterally non-aligned and aligned conditions because the virtual environment tested already showed an inherent perceptual distortion in depth. This distortion in depth may have affected manipula-

tion performance under laterally aligned as well as laterally non-aligned conditions. The mis-alignment in depth may even have dominated the effects of lateral mis-alignment. To isolate the effects of lateral mis-alignments the experiments should be carried out in a perfectly calibrated virtual environment. For now, we conclude that the misalignments of current VE systems as studied in our experiments do not affect manipulation performance.

5 CONCLUSIONS

- After-effects of adapted eye-hand coordination during VE immersion with perceptually misaligned virtual hand position were revealed by the outcome of pointing tasks during subjective calibration, pre- and post-tests. Pre-tests revealed open-loop pointing errors that serve as a base-line for interpreting the results of pointing tasks in VE (subjective calibration) and during post-tests (showing after-effects). A comparison of subjective calibration and pre-tests showed perceptual distortions of virtual space. A comparison of post-tests and pre-tests showed after-effects of adaptation of eye-hand coordination due to VE immersion.

- After-effects in the *lateral* direction were found *opposite* to the shift of virtual hand position during immersion. This *negative* after-effect was significant under stereoscopic conditions and had a magnitude of 20% of the lateral shift. Under monoscopic conditions no significant after-effects were found.

- After-effects found for the depth dimension were opposite to the 50% perceptual minification of virtual space as shown by the subjective calibration test. However, this *negative* after-effect did not scale with the target distance for pointing. Instead, the after-effect was constant with a magnitude of 4 cm. This after-effect is likely to be caused by either perceptual distortions of visual space due to HMD optics, or to eye-muscle potentiation just after immersion. Further studies are needed to discriminate between possible causes.

- Manipulation performance was not affected by lateral shifts of the virtual hand. Even when the virtual hand was perceived at another position than the real hand, the completion time and accuracy of grasping and positioning tasks did not significantly differ from identical tasks under aligned conditions.

- The occurrence of negative after-effects in lateral direction is a proof of lower level parameter adjustment in eye-hand coordination. This is promising for those interested in using virtual hands to acquire visuo-motor skills. Acquired skills in VE are likely to transfer to the real world.

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15. **ABSTRACT (MAXIMUM 200 WORDS (1044 BYTES))**

Virtual hand control is a direct natural manipulation method in virtual environments enabling advanced applications in the field of interactive design, training, medicine, etc. TNO researchers (Werkhoven & Groen, 1997) have shown that for grasping and positioning tasks virtual hand control is faster and more accurate than traditional mouse/cursor interactions. However, in virtual environments the virtual hand may not always be exactly aligned with the real hand. Such misalignment may cause an adaptation of the users' eye-hand coordination. Further, misalignment may cause a decrease in manipulation performance compared to aligned conditions.
This experimental study uses a prism adaptation paradigm to explore visuo-motor adaptation to misaligned virtual hand position. Participants were immersed in an interactive virtual environment with a deliberately misaligned virtual hand position (a lateral shift of 10 cm). We carried out pointing tests with a non-visible hand in the real world before (pre-test) and after (post-test) immersion in the virtual world.
A comparison of pre- and post-tests revealed after-effects of the adaptation of eye-hand coordination in the opposite direction of the lateral shift (negative after-effects). The magnitude of the after-effect was 20% under stereoscopic viewing conditions. However, decreased manipulation performance in VE (speed/accuracy) during the immersion with misaligned hand conditions was not found.
The occurrence of negative after-effects in lateral direction indicates that adaptation is not explained by a strategic change of eye-hand coordination but by a lower-level parameter adjustment. Therefore, acquired visuo-motor skills in VE are likely to transfer to the real world.

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